

Technical Memorandum G-161-9

MODIFICATIONS OF THE WIDEBAND FM TDRS SYSTEM

by

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ABSTRACT

This is one of a series of reports on the wideband FM modulation scheme for the Tracking and Data Relay Satellite (TDRS) system. The technique achieves a spread-spectrum advantage against multipath and interference through the inclusion of a large deviation FM subcarrier. The signal also permits co-channel spread-spectrum multiple access (SSMA) on the downlink from mission spacecraft to TDRS. Each user is assigned a unique combination of carrier and subcarrier which allows the ground receiver to separate user signals with overlapping spectra.

The system described in memorandum G-161-8 is modified by the addition of a low-deviation fine range tone to both the uplink and the downlink, separate from the wide-deviation subcarrier. Thereby simplifications and greater flexibility are made possible in both the transponder and the ground receiver. The magnitude of the interference components due to other SSMA signals are analyzed. A new carrier and subcarrier frequency plan is worked out based on the modified signal format. A configuration to accommodate 42 and 60 users is described. The inclusion of ambiguity resolving ranging sidetones is also discussed.

For the uplink involving multiple relay satellites it is proposed that each TDRS is assigned a separate subcarrier frequency, but transmits on the same carrier frequency. The same ranging sidetones and command data are relayed through each TDRS. The user receives and demodulates all of the TDRS signals, but transponds the ranging sidetones from only one of the TDRS satellites in accordance with a command from the ground. The uplink TDRS subcarrier frequencies will be selected on the basis of minimizing interference from external transmitters, other TDRS signals, and diffuse multipath.

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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION	1
2 MODIFIED SSMA ANALYSIS	4
2.1 Downlink Case	4
2.2 Uplink Case.	17
3 MODIFIED USER CHANNEL ALLOCATION TECHNIQUE. . .	21
3.1 Downlink Case	21
3.2 Uplink Case.	23
Appendix A A USER CHANNEL ALLOCATION TECHNIQUE WITH SIDETONE RANGING MODULATION	24

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MODIFICATIONS OF THE WIDEBAND FM TDRS SYSTEM

1. INTRODUCTION AND SUMMARY

This Technical Memorandum describes modifications of the wideband FM TDRS system arising as a result of analyses described in Technical Memorandum G-161-8. In particular, we consider the addition of a fine range tone to both the uplink and the downlink basebands, separate from the wideband subcarrier. This range tone phase modulated the carrier with a low deviation (on the order of 0.5 - 1.0 radians) and results in a significant increase in system flexibility. While the signal structure is correspondingly more complex, system complexity may actually be reduced compared to the unmodified system concept.

The advantages of this modification are:

1. A single range tone frequency for all users permits identical ranging precision for all users, and identical range measurement units for all users in the ground receiver.
2. The use of a separate range tone means that the downlink and uplink subcarriers do not have to be coherent. This permits use of a standardized downlink subcarrier synthesizer for all users and permits the downlink subcarrier frequency of each user to be selected on command from the ground. This highly useful possibility can be used to increase system user capacity.

3. On the uplink each TDRS would be assigned a different subcarrier frequency for access into the user transponder. These subcarrier frequencies, one for each TDRS, can be chosen so as to minimize interference on the uplink from other TDRS signals and external earth-based transmitters. This is a significant advantage of this modification, and of Teledyne ADCOM's wideband FM technique when compared to other spread-spectrum approaches.
4. If the range tone frequency is taken to be 128 kHz, and the downlink subcarrier frequency separation is 4 kHz (rather than 10 kHz as in Technical Memorandum G-161-8) 42 users can be accommodated in 3 carrier frequency bands separated by 20 kHz. The number of subcarrier frequencies in each band is 14, ranging from 80 kHz to 136 kHz in 4 kHz steps, with the 128 kHz frequency reserved for the range tone. If two additional carrier bands are added as new outer carrier frequency bands, it will be possible to accommodate 9 users in each band, with subcarrier frequencies in these bands ranging within 100-136 kHz, for a total of 60 users.
5. Finally, the additional desired-user intermodulation components and SSMA other-user interference caused by the addition of a low deviation range tone can be made essentially negligible. Of course, the lower downlink subcarrier frequency spacing which was necessitated by the use of a separate range tone, and the greater number of users, may result in increased SSMA other-user interference.

In Sec. 2 of this Technical Memorandum, we examine the desired-user/single other-user SSMA situation for the case where the downlink carrier is phase-modulated by split-phase binary data, a single fine range tone, and a wide deviation subcarrier. This analysis is then modified to apply to the uplink case where several different TDRS signals are received simultaneously in the same 148.0 - 149.9 MHz band. The various desired-user intermodulation components are identified and their effects on system performance analyzed. The additional other-user interference components caused by the presence of the range tone are identified and their amplitudes computed. It is these additional components which will be shown to be negligible for a range tone phase deviation on the order of 0.5 to 1.0 radian.

In Sec. 3 the modified downlink user channel allocation technique is presented. This technique is able to accommodate 42 users with 3 different carrier bands and 14 different subcarrier frequencies. The addition of 2 extra carrier bands, accommodating 9 different subcarrier frequencies in each band raises the total user capacity to 60 simultaneous users. The corresponding modifications required in the uplink are also presented in Sec. 3.

Finally, the case where ambiguity-range tones are added in a widetone ranging modulation techniques is described in Appendix A.

2. MODIFIED SSMA ANALYSIS

2.1 Downlink Case

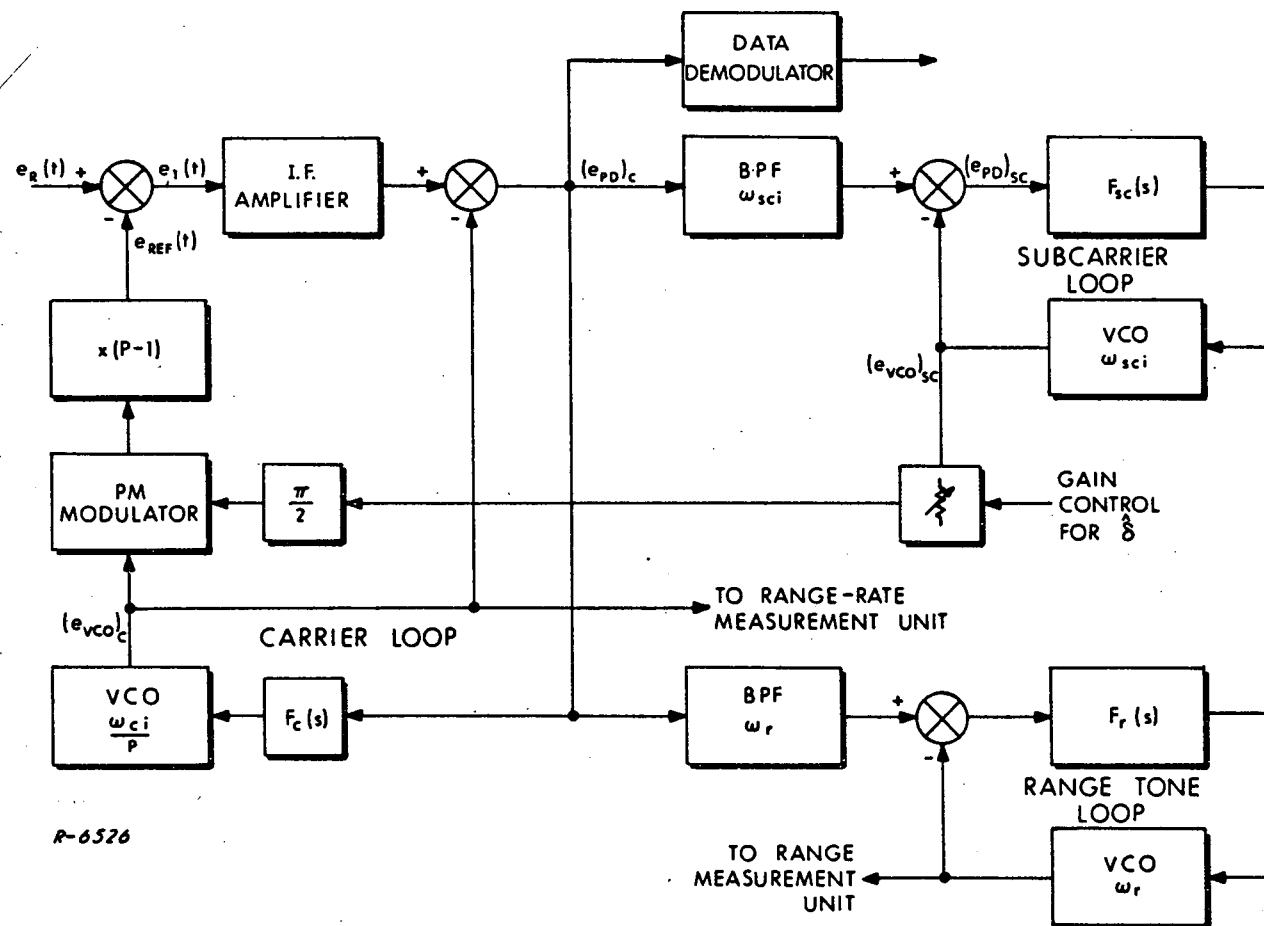
A block diagram of the modified ground receiver used to receive the i^{th} user transmission is shown in Fig. 1. The modification involves addition of a range tone loop to track the coherently transponded range tone.

The received signal in this case (for a single other user) is

$$e_R(t) = E_i \sin \left\{ \omega_{ci} t_i' + \beta x_i(t_i') + \rho \sin[\omega_r t_i'] + \delta \sin[\omega_{sci} t_i'] \right\} \\ + E_k \sin \left\{ \omega_{ck} t_k' + \beta x_k(t_k') + \rho \sin[\omega_r t_k'] + \delta \sin[\omega_{sck} t_k'] \right\} \quad (1)$$

where

- E_i = the amplitude of the i^{th} user receiver signal
- E_k = the amplitude of the k^{th} user received signal
- ω_{ci} = transmitted carrier frequency of the i^{th} user
- ω_{ck} = transmitted carrier frequency of the k^{th} user
- ω_{sci} = transmitted subcarrier frequency of the i^{th} user
- ω_{sck} = transmitted subcarrier frequency of the k^{th} user
- ω_r = range tone frequency
- β = phase deviation of the data on the carrier
- ρ = range tone phase deviation on carrier



R-6526

Fig. 1 Block Diagram of Modified Ground Receiver for i^{th} User

- δ = subcarrier phase deviation on carrier
 $x_i(t)$ = split-phase binary data of the i^{th} user
 $x_k(t)$ = split-phase binary data of the k^{th} user
 t'_i = $t - t_{di}$, where t_{di} is the direct-path time varying time delay of the i^{th} user.
 t'_k = $t - t_{dk}$, where t_{dk} is the direct-path time varying time delay of the k^{th} user.

The reference signal for the i^{th} user, $e_{\text{REF}}(t)$ is

$$e_{\text{REF}}(t) = \cos \left\{ \left(\frac{P-1}{P} \right) [\omega_{ci} t'_i - \theta_{ci}] + \hat{\delta} \sin [\omega_{sci} t'_k - \theta_{sci}] \right\} \quad (2)$$

and the carrier loop VCO signal is

$$(e_{\text{VCO}})_c = \cos \left\{ \frac{1}{P} [\omega_{ci} t'_i - \theta_{ci}] \right\} \quad (3)$$

so that the output of the carrier loop phase detector is

$$\begin{aligned}
 (e_{\text{PD}})_c = & E_i \sin \left\{ \theta_{ci} + \beta x_i(t'_i) + \rho \sin [\omega_r t'_i] \right. \\
 & \left. + \delta \sin [\omega_{sci} t'_i] - \hat{\delta} \sin [\omega_{sci} t'_i - \theta_{sci}] \right\} \\
 & + E_k \sin \left\{ \theta_{ci} + (\omega_{ck} t'_k - \omega_{ci} t'_i) + \beta x_k(t'_k) + \rho \sin [\omega_r t'_k] \right. \\
 & \left. + \delta \sin [\omega_{sck} t'_k] - \hat{\delta} \sin [\omega_{sci} t'_i - \theta_{sci}] \right\} \quad (4)
 \end{aligned}$$

As in Technical Memorandum G-161-8, the i^{th} user subcarrier difference is written as

$$\begin{aligned} \hat{\delta} \sin[\omega_{\text{sci}} t'_i - \theta_{\text{sci}}] - \delta \sin[\omega_{\text{sci}} t'_i] &= \\ &= \Delta_{\text{sc}} \sin[\omega_{\text{sci}} t'_i - \theta_{\text{sci}} - \phi_{\text{sci}}] \end{aligned} \quad (5)$$

where

$$\Delta_{\text{sc}} = \left\{ (\hat{\delta} - \delta)^2 + 4 \hat{\delta} \delta \sin^2 \left(\frac{\theta_{\text{sci}}}{2} \right) \right\}^{1/2} \quad (6)$$

$$\sin \phi_{\text{sci}} = \frac{\delta}{\Delta_{\text{sc}}} \sin \theta_{\text{sci}} \quad (7)$$

$$\sin(\theta_{\text{sci}} + \phi_{\text{sci}}) = \frac{\hat{\delta}}{\Delta_{\text{sc}}} \sin \theta_{\text{sci}} \quad (8)$$

The k^{th} user subcarrier difference is not written as a single resultant component because the k^{th} user subcarrier frequency is different from the i^{th} user subcarrier frequency. If the k^{th} user subcarrier frequency is the same as that of the i^{th} user (except for small doppler), a representation of the subcarrier difference as a single resultant component is useful. In this case the carrier frequencies will be different, and this will prevent other-user interference.

With the use of Eq. (5), $(e_{\text{PD}})_c$ becomes

$$\begin{aligned} (e_{\text{PD}})_c &= E_i \sin \left\{ \theta_{\text{ci}} + \beta x_i(t'_i) + \rho \sin[\omega_{\text{ri}} t'_i] \right. \\ &\quad \left. - \Delta_{\text{sc}} \sin[\omega_{\text{sci}} t'_i - \theta_{\text{sci}} - \phi_{\text{sci}}] \right\} \\ &+ E_k \sin \left\{ \theta_{\text{ci}} + (\omega_{\text{ck}} t'_k - \omega_{\text{ci}} t'_i) + \beta x_i(t'_i) + \rho \sin[\omega_{\text{ri}} t'_i] \right. \\ &\quad \left. + \delta_k \sin[\omega_{\text{sck}} t'_k] - \hat{\delta}_i \sin[\omega_{\text{sci}} t'_i - \theta_{\text{sci}}] \right\} \end{aligned} \quad (9)$$

The desired-user component of $(e_{PD})_c$ is expanded, as in Technical Memorandum G-161-8, as

$$\begin{aligned}
 & + E_i J_0(\Delta_{sc}) \sin \left\{ \theta_{ci} + \beta x_i(t'_i) + \rho \sin [\omega_{ri} t'_i] \right\} \\
 & - E_i 2 J_1(\Delta_{sc}) \cos \left\{ \theta_{ci} + \beta x_i(t'_i) + \rho \sin [\omega_{ri} t'_i] \right\} \times \\
 & \quad \times \sin [\omega_{sci} t'_i - \theta_{sci} - \phi_{sci}] \\
 & + E_i 2 J_2(\Delta_{sc}) \sin \left\{ \theta_{ci} + \beta x_i(t'_i) + \rho \sin [\omega_{ri} t'_i] \right\} \\
 & \quad \times \cos [2(\omega_{sci} t'_i - \theta_{sci} - \phi_{sci})] + \dots \quad (10)
 \end{aligned}$$

Components involving $J_n(\Delta_{sc})$ for $n \geq 3$ may be neglected for Δ_{sc} on the order of 1 radian or less. Likewise, with Eq. (10) expanded as

$$\begin{aligned}
 & E_i J_0(\Delta_{sc}) \sin \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \left[J_0(\rho) + 2 J_2(\rho) \cos [2 \omega_{ri} t'_i] + \dots \right] \\
 & + E_i J_0(\Delta_{sc}) \cos \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \left[2 J_1(\rho) \sin [\omega_{ri} t'_i] + \dots \right] \\
 & - E_i 2 J_1(\Delta_{sc}) \cos \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \left[J_0(\rho) + 2 J_2(\rho) \cos [2 \omega_{ri} t'_i] + \dots \right] \times \\
 & \quad \times \sin [\omega_{sci} t'_i - \theta_{sci} - \phi_{sci}] \\
 & + E_i 2 J_1(\Delta_{sc}) \sin \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \left[2 J_1(\rho) \sin [\omega_{ri} t'_i] + \dots \right] \times \\
 & \quad \times \sin [\omega_{sci} t'_i - \theta_{sci} - \phi_{sci}]
 \end{aligned}$$

$$\begin{aligned}
& + E_i 2 J_2(\Delta_{sc}) \sin \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \left[J_0(\rho) + 2 J_2(\rho) \cos [2 \omega_{ri} t'_i] + \dots \right] \\
& \quad \times \cos [2 (\omega_{sci} t'_i - \theta_{sci} - \phi_{sci})] \\
& + E_i 2 J_2(\Delta_{sc}) \cos \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \left[2 J_1(\rho) \sin [\omega_{ri} t'_i] + \dots \right] \times \\
& \quad \times \cos [2 (\omega_{sci} t'_i - \theta_{sci} - \phi_{sci})] \quad , \quad (11)
\end{aligned}$$

components involving $J_n(\rho)$ for $n \geq 3$ may also be neglected, since ρ is on the order of 0.5 to 1.0 radian. Of interest here are the desired components listed below, plus possible intermodulation components which could interfere with the desired components. The desired components are:

carrier loop error signal

$$E_i J_0(\Delta_{sc}) J_0(\rho) \cos \beta \sin \theta_{ci} \quad (12)$$

data signal

$$E_i J_0(\Delta_{sc}) J_0(\rho) \sin \beta \cos \theta_{ci} x_i(t'_i) \quad (13)$$

range tone

$$E_i J_0(\Delta_{sc}) \cos \beta \cos \theta_{ci} 2 J_1(\rho) \sin [\omega_{ri} t'_i] \quad (14)$$

subcarrier

$$- E_i 2 J_1(\Delta_{sc}) \cos \beta \cos \theta_{ci} J_0(\rho) \sin [\omega_{sci} t'_i - \theta_{sci} - \phi_{sci}] \quad (15)$$

The intermodulation components are:

range tone

$$- E_i J_0(\Delta_{sc}) 2 J_1(\rho) (\sin \theta_{ci}) \sin \beta x_i(t'_i) \sin [\omega_{ri} t'_i] \quad (16)$$

subcarrier

$$+ E_i 2J_1(\Delta_{sc}) J_0(\rho) (\sin \theta_{sc}) \sin \beta x_i(t'_i) \sin [\omega_{sci} t'_i - \theta_{sci} - \phi_{sci}] \quad (17)$$

These intermodulation components may be neglected because:

- a. with θ_{ci} small, $\sin \theta_{ci}$ is small, and
- b. with $x_i(t'_i)$ being split-phase binary, very little data power will lie within the narrow subcarrier and range tone loop noise bandwidths.

Since $\omega_{sci} \neq \omega_r$ for all users, the other intermodulation components of any concern are:

$$E_i 2J_1(\Delta_{sc}) J_2(\rho) \cos \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \sin [(2\omega_r - \omega_{sci}) t'_i + \theta_{sci} + \phi_{sci}]$$

$$\text{if } (2\omega_r - \omega_{sci}) = 0 \text{ or } -\omega_r \quad (18)$$

and

$$- E_i 2J_2(\Delta_{sc}) J_1(\rho) \cos \left\{ \theta_{ci} + \beta x_i(t'_i) \right\} \sin [(2\omega_{sci} - \omega_r) t'_i - \theta_{sci} - \phi_{sci}]$$

$$\text{if } (2\omega_{sci} - \omega_r) = 0 \text{ or } -\omega_{sci} \quad (19)$$

If $2\omega_r > \omega_{sci}$ for all users, it is impossible for

$$(2\omega_r - \omega_{sci}) = 0, -\omega_r \quad (20)$$

Likewise, if $2\omega_{sci} > \omega_r$ for all users, it is impossible for

$$(2\omega_{sci} - \omega_r) = 0, -\omega_{sci} \quad (21)$$

In words, there will be no desired-user intermodulation of any consequence, if

1. The range tone frequency is chosen to be different from any of the downlink subcarrier frequencies.

2. The range tone frequency is greater than one-half the largest downlink subcarrier frequency.
3. The range tone frequency is less than twice the lowest downlink subcarrier frequency.

The other user component of $(e_{PD})_c$ is expanded, as in Technical Memorandum G-161-8, as

$$E_k \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} J_n(\hat{\delta}) J_p(\rho) \sin \left\{ \theta_{ci} + \beta x_k(t'_k) + (\omega_{ck} t'_k - \omega_{ci} t'_i) + [n\omega_{sck} t'_k - m(\omega_{sci} t'_i - \theta_{sci}) + p\omega_r t'_k] \right\} \quad (22)$$

Only values of p equal to 0, ± 1 , and ± 2 will be considered. Only those components of Eq. (22) which lie near dc, or near ω_{sci} , or near ω_r can actually cause interference.

For interference components near dc, the normalized amplitudes

$$\frac{J_n(\delta) J_m(\hat{\delta}) J_p(\rho)}{J_o(\Delta_{sc})} \frac{J_p(\rho)}{J_o(\rho)} = \frac{J_n(\delta) J_m(\hat{\delta})}{J_o(\hat{\delta} - \delta)} \frac{J_p(\rho)}{J_o(\rho)} \quad (23)$$

are the important factors which determine the severity of the other-user interference from the n, m, p component. The values of δ and $\hat{\delta}$ are chosen (See Technical Memorandum G-161-8) as $\delta = 5.12$ and $\hat{\delta} = 5.52$, so that the values of

$$\left| \frac{J_n(\delta) J_m(\hat{\delta})}{J_o(\hat{\delta} - \delta)} \right| \quad (24)$$

are those given in Table 1. These values apply to Eq. (23) for $p=0$. If components, for which the absolute values of the normalized amplitudes of Eq. (23) are less than 0.04, may be neglected, then

n \ m	0	1	2	3	4	5	6	7	8	9
0	0.0000	0.0488	0.0177	0.0360	0.0567	0.0463	0.0271	0.0127	0.0050	0.0017
1	0.0000	0.1200	0.0435	0.0885	0.1396	0.1139	0.0667	0.0311	0.0122	0.0041
2	0.0000	0.0019	0.0007	0.0014	0.0022	0.0018	0.0010	0.0005	0.0002	0.0001
3	0.0000	0.1214	0.0440	0.0896	0.1413	0.1153	0.0675	0.0315	0.0123	0.0042
4	0.0000	0.1404	0.0509	0.1036	0.1634	0.1333	0.0781	0.0364	0.0143	0.0048
5	0.0000	0.0980	0.0355	0.0723	0.1140	0.0930	0.0545	0.0254	0.0100	0.0034
6	0.0000	0.0510	0.0185	0.0376	0.0593	0.0484	0.0283	0.0132	0.0052	0.0018
7	0.0000	0.0215	0.0078	0.0158	0.0250	0.0204	0.0119	0.0056	0.0022	0.0007
8	0.0000	0.0077	0.0028	0.0056	0.0089	0.0073	0.0043	0.0020	0.0008	0.0003
9	0.0000	0.0047	0.0017	0.0035	0.0055	0.0045	0.0026	0.0012	0.0005	0.0002

Table 1 $\left| \frac{J_n(\delta) J_m(\hat{\delta})}{J_0(\hat{\delta} - \delta)} \right|$ for $\delta = 5.12$ $\hat{\delta} = 5.52$

n \ m	0	1	2	3	4	5	6	7	8	9
0		0.0488			0.0567	0.0463				
1		0.1200	0.0435	0.0885	0.1396	0.1139	0.0667			
2										
3		0.1214	0.0440	0.0896	0.1413	0.1153	0.0675			
4		0.1404	0.0509	0.1036	0.1634	0.1333	0.0781			
5		0.0980		0.0723	0.1140	0.0930	0.0545			
6		0.0510			0.0593	0.0484				
7										
8										
9										

Table 2

$$\frac{J_n(\delta) J_m(\hat{\delta})}{J_o(\hat{\delta} - \delta)}$$

for Non-Negligible Other-User
Interference Components for $\delta=5.12$
and $\hat{\delta} = 5.52$

for $p=0$ only the components indicated in Table 2 need be considered further.

If $\rho = 0.5$ radians, $J_1(\rho)/J_0(\rho) = 0.2423/0.9385 = 0.258$. The largest value of Eq. (24) is 0.1634 for $n=m=\pm 4$. The absolute value of the $n=m=\pm 4$, $p=\pm 1$ components is therefore 0.0422. All other components have absolute values of Eq. (23) which are less than 0.04, and may therefore be neglected. Consequently, all components for $p = \pm 2$ are also negligible.

Turning now to the interference components near the range tone frequency, ω_r , the normalized amplitudes

$$\frac{J_n(\delta)J_m(\hat{\delta})}{J_0(\Delta_{sc})} \frac{J_p(\rho)}{2J_1(\rho)} = \frac{J_n(\delta)J_m(\hat{\delta})}{J_0(\hat{\delta} - \delta)} \frac{J_p(\rho)}{2J_1(\rho)} \quad (25)$$

are the important factors which determine the severity of the other-user interference from the n, m, p component. The biggest problem arises from the $p=0$ components, since for $\rho=0.5$, $J_0(\rho)/2J_1(\rho) = 0.9385/2(0.2423) = 1.93$, and the absolute values of the normalized amplitudes for these components are essentially twice the values of Table. 1. For the $p = \pm 1$ components, the absolute values of the normalized amplitudes are one-half the values of Table 1. For the $p = \pm 2$ components, the absolute values of the normalized amplitudes are equal to 0.0625 times the values of Table 1. Consequently the $p = \pm 2$ components are negligible. Since the range tone loop noise bandwidth is much smaller than the carrier loop noise bandwidth, the problem of interference with range tone tracking from the $p=0$ components is not as severe as might appear at first glance.

If $\rho = 1.0$ radian, $J_0(\rho)/2J_1(\rho) = 0.7652/2(.4401) = 0.87$. This would reduce the severity of the problem of other-user interference with range tone tracking. In this case $J_1(\rho)/J_0(\rho)$ is 0.574, and the problem of other-user interference with carrier tracking and data demodulation is increased somewhat. Consequently, a value of ρ between 0.5 and 1.0 would appear to be in order.

To determine the effects of other-user interference on sub-carrier tracking, the output of the subcarrier loop phase detector must be examined. With the subcarrier loop VCO signal given by

$$(e_{VCO})_{sc} = \cos \{ \omega_{sci} t'_i - \theta_{sci} \} \quad (26)$$

the output of the subcarrier loop phase detector is

$$E_i 2 J_1(\Delta_{sc}) \cos \beta \cos \theta_{ci} J_0(\rho) \sin \phi_{sci}$$

plus the near dc components of

$$\begin{aligned} & E_k \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} J_n(\delta) J_m(\hat{\delta}) J_p(\rho) 2 \cos \{ \omega_{sci} t'_i - \theta_{sci} \} \times \\ & \times \sin \{ \theta_{ci} + \beta x_k(t'_k) + (\omega_{ck} t'_k - \omega_{ck} t'_i) + [n\omega_{sck} t'_k - m(\omega_{sci} t'_i - \theta_{sci}) + p\omega_r t'_k] \} \\ & = E_i 2 J_1(\Delta_{sc}) \cos \beta \cos \theta_{ci} J_0(\rho) \frac{\delta}{\Delta_{sc}} \sin \theta_{sci} \end{aligned}$$

plus the near dc components of

$$E_k \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} J_n(\delta) J_m(\hat{\delta}) J_p(\rho) \times$$

$$\begin{aligned}
& \times \left\{ \sin \left\{ \theta_{ci} + \beta x_k(t'_k) + (\omega_{ck} t'_k - \omega_{ci} t'_i) + \left[n\omega_{sck} t'_k - (m-1)(\omega_{sci} t'_i - \theta_{sci}) + p\omega_r t'_k \right] \right\} \right. \\
& \left. + \sin \left\{ \theta_{ci} + \beta x_k(t'_k) + (\omega_{ck} t'_k - \omega_{ci} t'_i) + \left[n\omega_{sck} t'_k - (m+1)(\omega_{sci} t'_i - \theta_{sci}) + p\omega_r t'_k \right] \right\} \right\} \\
& \quad (27)
\end{aligned}$$

Here the normalized amplitudes

$$\frac{J_n(\delta) J_m(\hat{\delta})}{\left(\frac{2J_1(\Delta_{sc})}{\Delta_{sc}} \right) \delta} \frac{J_p(\rho)}{J_o(\rho)} = \frac{J_n(\delta) J_m(\hat{\delta})}{\left(\frac{2J_1(\hat{\delta}-\delta)}{(\hat{\delta}-\delta)} \right) \delta} \frac{J_p(\rho)}{J_o(\rho)} \quad (28)$$

are the important factors which determine the severity of the other-user interference from the n, m, p component. This may be written as

$$\left[\frac{J_n(\delta) J_m(\hat{\delta})}{J_o(\hat{\delta}-\delta)} \frac{J_p(p)}{J_o(p)} \right] \left(\frac{1}{\delta} \right) \left[\frac{J_o(\hat{\delta}-\delta)}{2J_1(\hat{\delta}-\delta)/(\hat{\delta}-\delta)} \right] \quad (29)$$

The first factor is recognized as the normalized amplitudes of Eq. (23). The last factor is approximately equal to 1 for small $\hat{\delta} - \delta$. For the case where $\hat{\delta} - \delta = 0.4$, this factor is

$$\left[\frac{J_o(\hat{\delta}-\delta)}{2J_1(\hat{\delta}-\delta)/(\hat{\delta}-\delta)} \right] = \frac{(0.9604)}{2(0.1960)/(0.4)} = 0.98 \quad (30)$$

The big difference is the factor $(1/\delta)$, which, for $\delta = 5.12$, is

$$\left(\frac{1}{\delta} \right) = \frac{1}{5.12} = 0.195 \quad (31)$$

The largest other-user interference normalized amplitudes are for $p=0$ (for $0.5 \leq \rho \leq 1.0$). From Table 1, the largest value of the first factor of Eq. (29) for $p=0$ is 0.1634, and occurs for $m=n = \pm 4$.

The factor $(1/\delta)$ reduces the $n=m=\pm 4, p=0$ component of Eq. (29) to 0.0318, which is essentially negligible. Consequently, the small values of the other-user interference normalized amplitudes in conjunction with the small subcarrier loop noise bandwidth minimize the effects of other-user interference on subcarrier tracking. This is essential because large errors in subcarrier tracking could throw the carrier loop, and hence the subcarrier and range tone loops, out of lock.

2.2 Uplink Case

In this case the SSMA problem arises from the fact that more than one TDRS is transmitting at the same time in the same frequency band (148.0 - 149.9 MHz). Each TDRS uses the same carrier frequency and the same range tone frequency. The data signal is the same for each TDRS. The different TDRS satellites are distinguished by different subcarrier frequencies. The users receive and process signals from all of the TDRS satellites, but transpond the carrier, subcarrier and range tone from only one of the TDRS satellite signals in accordance with a command from the ground.

The desired TDRS received signal and a single other TDRS received signal are written as

$$\begin{aligned} & E_i \sin \left\{ \omega_c t'_i + \beta x(t'_i) + \rho \sin[\omega_r t'_i] + \delta \sin[\omega_{sci} t'_i] \right\} \\ & + E_k \sin \left\{ \omega_c t'_k + \beta x(t'_k) + \rho \sin[\omega_r t'_k] + \delta \sin[\omega_{sck} t'_k] \right\} \end{aligned} \quad (32)$$

The desired TDRS reference signal is

$$e_{REF}(t) = \cos \left\{ \left(\frac{P-1}{P} \right) [\omega_c t_i - \theta_{ci}] + \hat{\delta} \sin[\omega_{sci} t'_i - \theta_{sci}] \right\} \quad (33)$$

and the corresponding carrier loop VCO signal is

$$(e_{\text{VCO}})_c = \cos \left\{ \frac{1}{P} [\omega_c t'_i - \theta_{ci}] \right\} \quad (34)$$

so that the output of the carrier loop phase detector is

$$\begin{aligned} (e_{\text{PD}})_c = & E_i \sin \left\{ \theta_{ci} + \beta x(t'_i) + \rho \sin [\omega_r t'_i] \right. \\ & + \delta \sin [\omega_{sci} t'_i] - \hat{\delta} \sin [\omega_{sci} t'_i - \theta_{sci}] \left. \right\} \\ & + E_k \sin \left\{ \theta_{ci} + \omega_c (t'_k - t'_i) + \beta x(t'_k) + \rho \sin [\omega_r t'_k] \right. \\ & + \delta \sin [\omega_{sck} t'_k] - \hat{\delta} \sin [\omega_{sci} t'_i - \theta_{sci}] \left. \right\} \end{aligned} \quad (35)$$

The i^{th} TDRS subcarrier difference is written as in Eq. (5), and the signals in Eq. (35) are expanded in an identical fashion as in the downlink case. Consequently, the same remarks concerning desired-user intermodulation and other-user SSMA interference on the downlink apply also to the uplink. The only differences are:

1. $\omega_{ck} = \omega_{ci} = \omega_c$
2. $x_k(t) = x_i(t) = x(t)$
3. $\delta = 6.3$ (instead of 5.12)
4. $\hat{\delta} = 5.5$ (instead of 5.52)*

* The difference between $\hat{\delta} = 5.5$ and 5.52 is insignificant.

The values of

$$\left| \frac{J_n(\delta) J_m(\hat{\delta})}{J_0(\hat{\delta} - \delta)} \right| \quad (36)$$

are given in Table 3 for $\delta = 6.3$ and $\hat{\delta} = 5.5$. The largest value is 0.1749 for $n = \pm 5$, $m = \pm 4$. However, since only three TDRS satellites (or at most four) are expected to be used, many interference components will not actually cause interference since their spectral locations, with such a small number of other TDRS signals, can be made to fall at frequencies which are sufficiently far away from desired TDRS spectral components to cause only negligible interference effects.

0
20

m \ n	0	1	2	3	4	5	6	7	8	9
0	0.0018	0.0903	0.0310	0.0677	0.1049	0.0849	0.0494	0.0230	0.0089	0.0030
1	0.0017	0.0840	0.0288	0.0630	0.0975	0.0789	0.0459	0.0213	0.0083	0.0028
2	0.0023	0.1169	0.0402	0.0225	0.1359	0.1099	0.0640	0.0297	0.0116	0.0039
3	0.0002	0.0097	0.0033	0.0073	0.0113	0.0091	0.0012	0.0025	0.0010	0.0003
4	0.0025	0.1262	0.0434	0.0947	0.1466	0.1186	0.0691	0.0321	0.0125	0.0042
5	0.0030	0.1505	0.0517	0.1129	0.1749	0.14150	0.0824	0.0383	0.0149	0.0050
6	0.0023	0.1127	0.0387	0.0845	0.1309	0.1059	0.0617	0.0286	0.0112	0.0038
7	0.0013	0.0643	0.0221	0.0482	0.0747	0.0604	0.0352	0.0163	0.0064	0.0021
8	0.0006	0.0301	0.0103	0.0226	0.0349	0.0283	0.0165	0.0076	0.0030	0.0010
9	0.0002	0.0096	0.0033	0.0072	0.0112	0.0091	0.0053	0.0024	0.0010	0.0003

Table 3 $\frac{J_n(\delta)J_m(\hat{\delta})}{J_0(\delta - \hat{\delta})}$ for $\delta = 6.3$ and $\hat{\delta} = 5.5$

3. MODIFIED USER CHANNEL ALLOCATION TECHNIQUE

3.1 Downlink Case

The addition of a low deviation range tone on the downlink necessitates some modification of the user channel allocation technique. This modification arises from the fact that the presence of the range tone increases the signal bandwidth by twice the range tone frequency.^{*} This necessitates a reduction in the subcarrier frequency spacing in order that the required number of users can be accommodated without using the high subcarrier frequencies. Use of the high subcarrier frequencies (140, 150, 160 kHz), as described in Technical Memorandum G-161-8, with a range tone frequency on the order of 100 kHz, would result in a spread spectrum bandwidth greater than the allotted 2 MHz bandwidth if the 6th order subcarrier sidebands are transmitted with their associated range tone first-order sidebands.

The following modifications of the user channel allocation technique are proposed:

1. The subcarrier frequency spacing is reduced from 10 kHz to 4 kHz.
2. The range tone frequency is selected as 128 kHz, since this is sufficiently high to yield adequate ranging precision, and has the added advantage of being equal to 32 times the 4 kHz subcarrier frequency spacing. This means that the range tone received by the user

^{*} Only the first-order range tone sidebands need be transmitted since the range tone is low deviation (0.5 - 1.0 radians) phase modulated on the carrier.

spacecraft on the uplink can be conveniently used to generate the downlink subcarrier.^{*} This permits the uplink subcarrier frequencies, used to distinguish between the different TDRS's to be chosen only on the basis of minimizing uplink interference from external co-channel transmitters, other TDRS signals, and diffuse multipath. This capability greatly increases the system design flexibility.

3. The downlink subcarrier frequencies are chosen to be 80, 84, 88, 92, 96, 100, 104, 108, 112, 116, 120, 124, 132 and 136 kHz for a total of 14.

If three carrier bands are used separated by 20 kHz and centered in the middle of the 2 MHz wideband, a total of 42 users can be accommodated with 14 users in each band. The addition of two more carrier bands, as indicated in Fig. 2, can result in a system capable of accommodating 60 simultaneous users. In this case the addition of the two outer carrier bands does not preclude the use of any of the 14 subcarrier frequencies in the inner three carrier bands. This means that the system can be initially designed with only the three inner carrier bands utilized, with the two outer bands added of and when increased system capacity requirements warrant.

One final problem which must be resolved is the question of how range ambiguity resolution is to be accomplished. This may be achieved with the aid of either additional range-ambiguity tones, or a range-ambiguity PN code. The addition of these range-ambiguity signals may necessitate another modification in the user

^{*} This is not necessary, however.

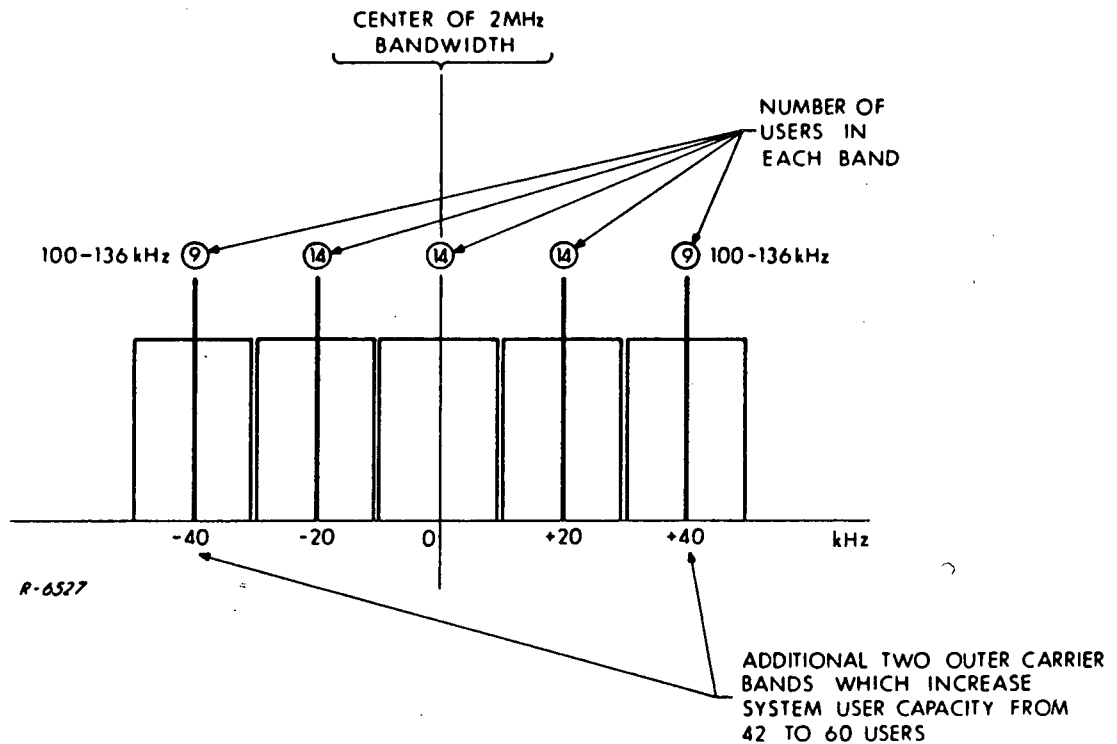


Fig. 2 Location of Carrier Frequency Bands for Case of Five Bands in Modified User Channel Allocation.

channel allocation technique. See Appendix A for one such possible modification.

3.2 Uplink Case

In the uplink each TDRS is assigned a separate subcarrier frequency, but transmits on the same carrier frequency. The same ranging sidetones and command data are relayed through each TDRS. The user receives and demodulates all of the TDRS signals, but transponds the ranging sidetones from only one of the TDRS satellites in accordance with a command from the ground. The uplink TDRS subcarrier frequencies are selected on the basis of minimizing interference from external transmitters, other TDRS signals, and diffuse multipath.

Appendix A

A USER CHANNEL ALLOCATION TECHNIQUE WITH SIDETONE RANGING MODULATION

In this appendix we consider a user allocation technique which may be used with a sidetone ranging modulation. This technique is capable of accommodating a maximum of 72 simultaneous users. A detailed description is given below.

<u>Range Tones:</u>	102.4 kHz	Fine Range Tone
	12.8 kHz	= $102.4 \text{ kHz} \div 8$
	1.6 kHz	= $12.8 \text{ kHz} \div 8$
Ambiguity Resolving Tones	400 Hz	= $1600 \text{ Hz} \div 4$
	100 Hz	= $400 \text{ Hz} \div 4$
	25 Hz	= $100 \text{ Hz} \div 4$ (optional)

Sidetone Ranging Modulation:

102.4 kHz	Fine Range Tone
89.6 kHz	= $(102.4 - 12.8) \text{ kHz}$
88 kHz	= $(89.6 - 1.6) \text{ kHz}$

The remaining ambiguity resolving tones are AM modulated on the 88 kHz sidetone, thereby producing ranging sidetone frequencies at

$$88 \pm 0.400 \text{ kHz} = 88.400 \text{ and } 87.600 \text{ kHz}$$

$$88 \pm 0.100 \text{ kHz} = 88.100 \text{ and } 87.900 \text{ kHz}$$

and $88 \pm 0.025 \text{ kHz} = 88.025 \text{ and } 87.975 \text{ kHz.}$

Subcarrier Frequency Separation: 3.2 kHz

Subcarrier Frequencies: 24 different frequencies

60.8, 64.0, 67.2, 70.4, 73.6, 76.8, 80.0, 83.2, 92.8,
96.0, 99.2, 105.6, 108.8, 112.0, 115.2, 118.4, 121.6,
124.8, 128.0, 131.2, 134.4, 137.6, 140.8, and 144.0 kHz

Carrier Bands: 3 separated by 20 kHz

An additional advantage of this allocation technique is that the 100 Hz range-ambiguity tone can be used as the uplink data clock source. This means that the 100 Hz range tone can be demodulated in the user transponder and used to synchronously detect the uplink command data. By frequency multiplying the 100 Hz range tone by 10, the resulting 1 kHz signal can be used to clock the downlink telemetry data. In the ground receiver, the received 100 Hz range tone can be frequency multiplied by 10 and used to synchronously detect the downlink telemetry data.